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THE COAXIAL SLOW SOURCE: A QUASI-STATIC FRC FORMATION CONCEPT

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I. Introduction: In present generation FRC devices the plasma poloidal flux is generated rapidly on an Alfvén time scale using pulsed, high-voltage (50-100 kV) technology.[1] In the next generation FRC experiments[2] the plasma formation region will be significantly larger (wall radius ~ 1 m) than current devices (wall radius ~ 0.25 m). The applied voltages (~ 400 kV) required for these experiments can present a formidable technological task. Of course a large device could be "multi-feed", reducing the voltage per capacitor bank by the number of feed points. However, this approach not only compounds the cost and complexity of an unattractive technology, but also stresses the endurance and patience of the experimentalist.

Accordingly, the development of a formation technique in which the FRC poloidal flux would evolve slowly on or near a resistive time scale, using low voltage technology, would significantly enhance the reactor viability of the FRC concept. At Los Alamos, a small effort in "slow source" development has existed for several years; early experiments[3] using rotating-magnetic-fields were carried out in colaboration with the concept originators in Australia, exploratory analytical studies of purly ohmically-heated FRCs have been reported[4,5], and the concept of generating an FRC between two coaxial theta-pinch coils has been proposed[6].

In our "coaxial slow source", the subject of this paper, the FRC is inductively formed in the annular space between two (or more) coaxial multi-turn coils. The FRC poloidal flux is generated by the transfer of flux initially contained within the inner coil. We consider only the electromagnetics of the system; the plasma physics of the formation process has not yet been included in the analysis. Electromagnetically, the fundamental requirements for the coaxial slow source are: (1) The annular plasma formation region should. initially, be relatively void of magnetic fields which could adversly affect the FRC equilibrium formation; (2) The plasma poloidal flux should evolve quasi-statically as the plasma heats and; (3) In order to permit translation out of the annular formation region, the plasma torus should not be enclosed by poloidal magnetic fields which also link the external coil structures.

II. Coaxial Slow-Source Arrangement It has been shown[7] that several different combinations of coil arrangements and power supply circuitry satisfy the electromagnetic requirements noted above. For simplicity we present here a two-coil design. A cross section of one half of a coaxial slow source is shown diagrammatically in Fig. 1. The millisecond risetimes of this device permit the use of metal (Inconel) vacuum chamber walls which have proved advantageous in controlling impurities in the RFP experiment at Los Alamos. Axially slotted, inner and outer conducting shells, in close proximity to the vacuum chamber walls, provide the uniform equilibrium fields. The currents in these shells allow the adjacent multi-turn coils to "appear" to function a signal-turn flux-conserving coils. In this design each mulit-turn coil is made up of four separate layers of 22 turns per layer. Various series and parallel arrangements of the coil layers allow variation of the system risetime from about 0.5 to 2 ms; the risetime range can be further extended by a simple change of the capacitance of the energy storage bank. The plasma is modeled as an incompressible flux conserving surface of zero internal flux.

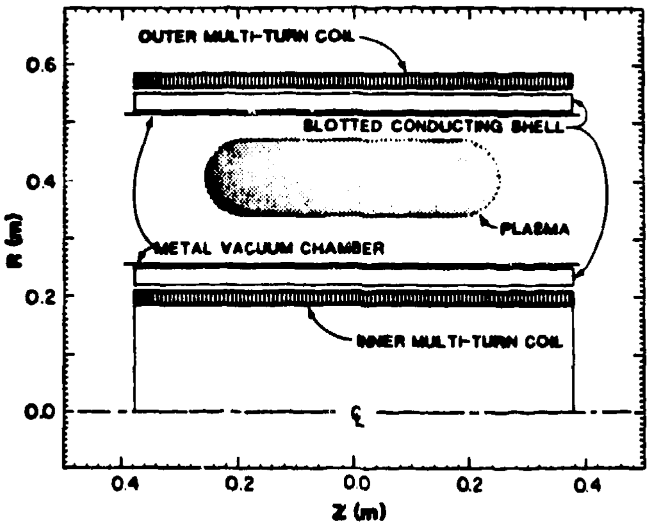

Figure 1

A schematic of the coaxial source electrical circuit is shown in Fig. 2. The inductive coupling between the circuit components has been included in the circuit analysis. The plasma inductance, which depends on the plasma volume and position within the annulus, is held constant, while the plasma resistance can be specified as a constant or a function of the plasma current. An isolating inductor (1.3 mH) is used between the two energy storage banks. Each bank is taken to be comprised of high energy-density, ignitron-switched capacitors with a total capacitance (per bank) of 3.4 mF. The maximum bank voltage is set at 10 kV.

III. Analytical Results The phenomenology of the two-coil coaxial slow source system can be observed from the inner-coil, outer-coil, and plasma-current waveforms shown in Fig. 3. There waveforms are generated by a circuit analysis code using the computer calculated mutual and self inductances of the system shown in Fig. 1. At time $t = 0$, the fluxing bank (charged to 8 kV) is fired, without plasma, and current flows into the inner and outer coils attaining peak values at time $t = t_1$. Since the voltages across the inner and outer coils are equal, the flux change is also the same within each coil, and with the coaxial coil arrangement net flux can only be contained within the inner coil. Accordingly, the annular space between the coils is relatively magnetic-field free, with the possible exception of small fringing fields near the device ends. The plasma is created at time $t = t_1$ (by some preionization technique), when the flux within the inner coil is maximum. After $t = t_1$, (without discharging any other capacitor banks) the current in the coils decreases, as the plasma current increases transfering the inner coil flux to poloidal plasma flux; the amount of flux transfer depending on the plasma and coil system geometry. In order to insure complete flux transfer, control the rate of flux transfer, and provide a voltage on the plasma at time $t = t_1$, a second capacitor bank (the plasma drive bank in Fig. 1) is

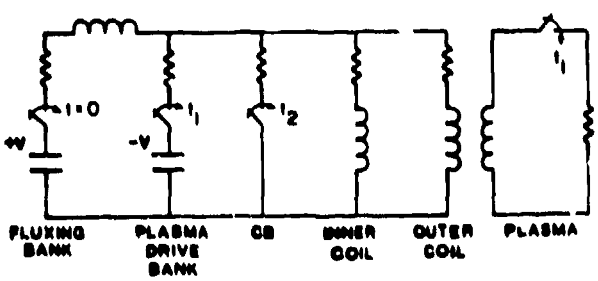

Figure 2

discharged across the parallel coil arrangement. The magnitudes of the plasma current and the coaxial coil currents are determined by the plasma-drive-bank charging voltage (9.2 kV in Fig. 3). At the proper charging voltage, the peak plasma current is equal and opposite in sign to the sum of number of coil turns times the coil currents (Fig.3). Thus the net current of the system is zero and magnetic field lines cannot enclose both the plasma and the coaxial coils. The system currents are crowbarred at time $t = t_2$ and the plasma can then be translated out of the formation region.

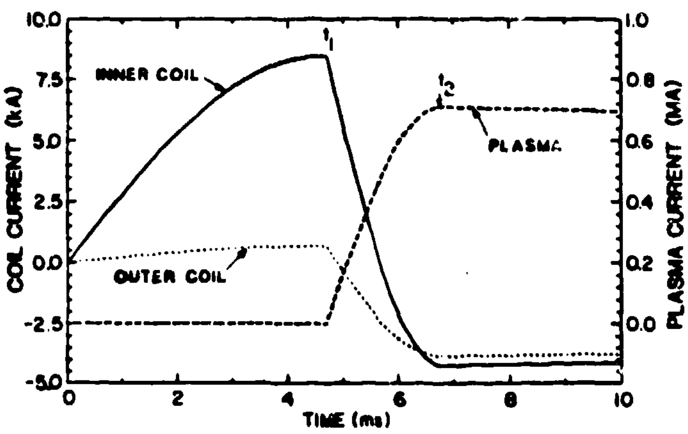

Figure 3

In calculating the currents shown in Fig. 3, the plasma resistance was set at a negligibly small value (1μΩ). Assuming classical resistive heating and no energy losses, the resistance (~ 20 mΩ) of an initially 2 eV plasma decreases rapidly to negligable values as the plasma heats. However if plasma energy losses restrict the plasma temperature to a few tens of eV then the plasma current decreases significantly; for a 45 eV plasma (R_p ~ 0.2 mΩ) the peak plasma current is about 50% of the 700 kA peak of Fig. 3.

The coaxial-slow-source, magnetic-flux-surface contours are calculated by a 2-D, axisymmetric code using the coil and plasma currents determined from the circuit analysis code. These contours are shown in Fig. 4 for three different times; (a) at peak inner coil flux (t = 4.7 ms, Fig. 3); (b) during the FRC formation phase (t = 5.7 ms) and; (c) at the end of the formation phase (t = 6.8 ms). The closed contours define regions of zero net poloidal flux. At the peak of the inner-coil current, nearly all the magnetic flux links both coils, and the plasma formation region is relatively void of magnetic fields. At the end of the formation phase essentially all of the magnetic flux, which originally passed through the inner coil, has been transfered into poloidal plasma flux, with no magnetic fields linking both the plasma and the coil structures. The radial profile of axial equilibrium magnetic fields obtained at this time is shown in Fig. 5 for z = 0 (the center of the coaxial slow source). The magnitude of the magnetic field is equal on both sides of the plasma at this time and at all times during the formation phase.

In summary, the elecromagnetics of one of several techniques for generating FRCs in a coaxial configuration has been presented. It has been shown that the discussed design satisfies all the electromagnetic requirements for a slow source. The next major issue is the investigation of the plasma physics which will ultimately determine the viability of this concept.

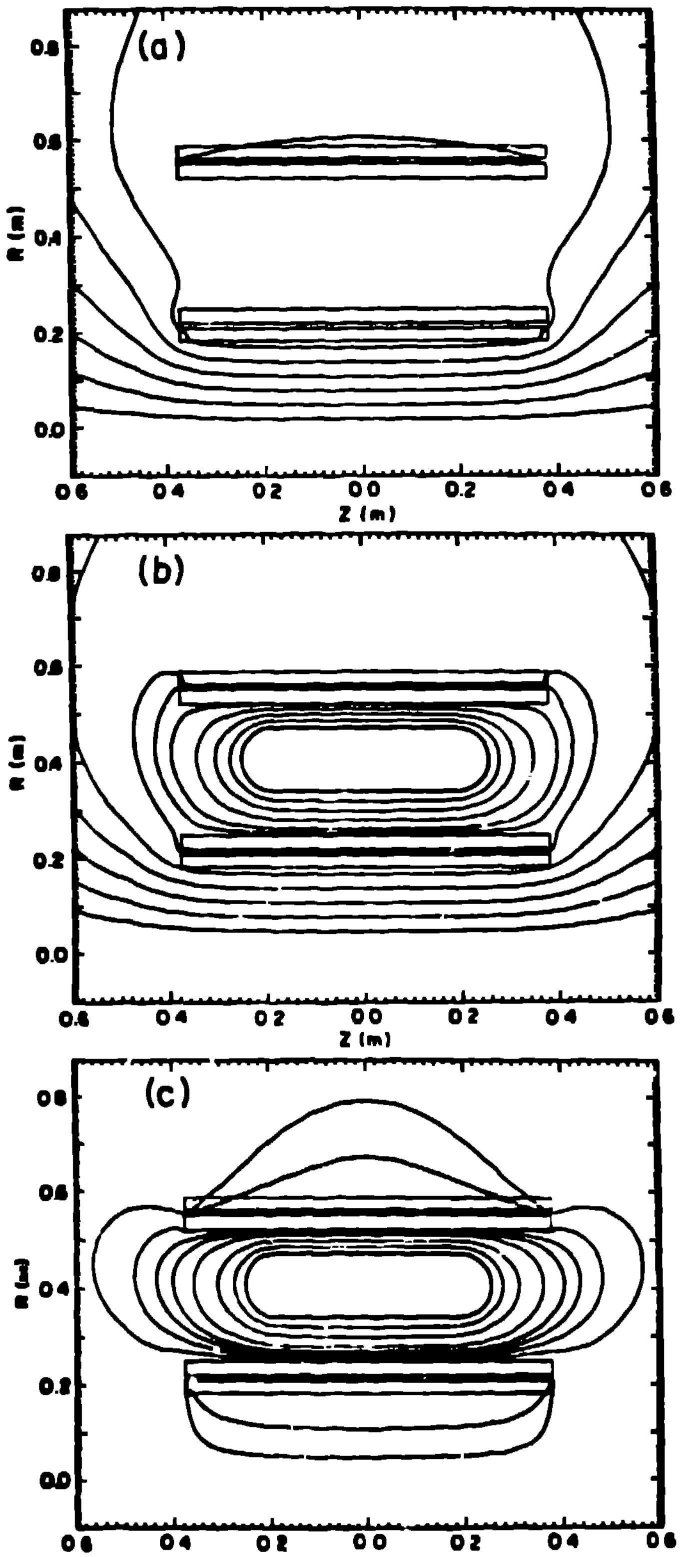

Figure 4

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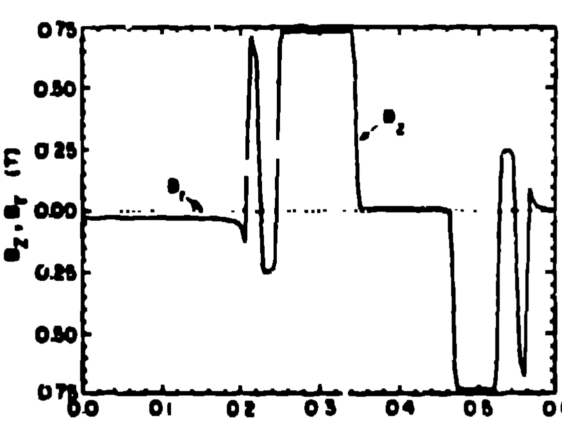

Figure 5